squall-line turbulence, but only when the center of depression has passed south of Colorado. This type of pressure distribution occurs more frequently in spring than in any other season of the year, but no season is free from it.

Other types of pressure distribution produce thunderstorms in this region, but only the types illustrated produce squall-line storms in that portion of New Mexico lying east of the continental divide.

The cold front, with its squall-line phenomena, as known in the eastern half of the United States, can not take shape in the mountainous region of the Southwest, where the front of an advancing cold current is broken up by mountain barriers into isolated streams that produce thunderstorms, only when there has been a previous importation of relatively moist air.

But a vigorous southward flow of cold air over the plains States reaches New Mexico with a well-defined cold front moving southwestward, along which decided squall-line phenomena often occurs.

The mountain ranges of central New Mexico mark the western limit of this type of squall line, so that over the larger portion of New Mexico importations of cold air are only in the form of narrow streams following the topographic depressions.

LATE TERTIARY CLIMATIC CHANGES IN OREGON

By EDWIN T. HODGE, Professor of Geology [University of Oregon]

Evidence is presented in this paper of five climatic changes in Oregon beginning in late Pliocene time and extending into Recent time. These changes have ranged between epochs characterized by extensive glaciation with a large supply of precipitation and epochs of limited glaciation and a comparatively small precipitation. The evidence presented in support of these conclusions may be found in the glacial and stream work on the uplands of the Cascade Mountains; in the valley profiles and deposits of streams on the west side of the Cascade Mountains and Willamette Valley; in coastal deposits; in widespread formations adjacent to the John Day, Deschutes, and Columbia Rivers; in these same canyons and their deposits; and in the silts and sands of Fossil Lake.

Each of these areas show five stages, but in only a few cases can a given stage be definitely shown to be identical with a stage of another area. The writer approves and presents reasons for the suggestion that the few stages of each area are in parallel series.

EAST SIDE OF CASCADE MOUNTAINS

Evidence of Stage II is to be found in The Dalles formation. The Dalles formation lies east of the Cascade Mountains and is of great importance in this study. (Fig. 1.) It is found east of the east fork of Hood River and extends in places to the Deschutes River. Small patches occur on the north side of the Columbia River east of the Klickitat River. South of Columbia River and beginning east of Mosier it occurs in great tongues lying in structural or erosional depressions. North of Fifteen Mile Creek and west of Deschutes River it almost covers the entire surface. Another great area lies west of the Deschutes River between Tygh Ridge and Mutton Mountains.

The Dalles formation is about 600 feet thick and is composed of well-bedded sediments and lavas. The sediments consist of water-worked glacial till, pumice, sand, gravels, and silts. The gravels and bowlders embedded in a volcanic sand show torrential cross-bedding. The andesitic lavas seal the other beds between and form a protective cover over them.

These beds lie nearly flat and fill all erosional and structural depressions. They completely obliterate the topography of the lowlands east of the Cascade Mountains and west of the Deschutes River. These structural characteristics of the beds suggests a Recent age for these deposits, but they must be older for they contain many glacial erratics.

For instance, near the city of The Dalles subangular, striated glacial erratics are abundant. They range in size from 15 feet in diameter to several inches in diameter. Associated with these are many subangular fragments which show no striation or polishing, but strongly suggest glacial origin. Some of these occur in a gray fluffy silt, wherein they have a most heterogeneous arrangement and look like true glacial deposits.

The larger fragments in The Dalles formation, which make up over 50 per cent of it, are clearly referable to Mount Hood. Furthermore, the materials can be traced almost to Mount Hood but not the entire distance. The interruption that defeats the complete tie is the east branch of Hood River Valley.

The Dalles formation, though it contains glacial erratics, is made up essentially of torrential materials. At the time this is written it is not certain whether glaciers extended as far eastward as The Dalles. It is quite likely that glaciers did reach 30 miles eastward from (say) Mount Hood, as shown by other morainal deposits mentioned below. The Dalles formation may be, therefore, either an outwash plain deposit, given off in front of glaciers on the Cascade Mountains, or aggradational deposits formed by streams active during a nonglacial stage following a glacial stage. For the purpose of the theory presented here it does not matter which origin is correct; the one essential fact is certain that an early glacial stage existed.

The glaciers that produced The Dalles formation, if they did not reach 30 miles eastward, at least extended far beyond the east fork of Hood River.

One of the most striking features regarding the Pleistocene, as of the present, is the evidence of intense glaciation on the east side of the Cascade Plateau. The presence of the glaciers at the present time is determined by the fact that the moist winds striking these mountains come from the west. During the ice age the prevailing winds were undoubtedly from the same direction, and a controlling factor in that glaciation was the superior altitude of the crest of the Cascade Mountains. The elevated crest robbed the winds of their moisture. Much of the snow falling from the chilled winds rising over the Cascade Range must have been carried by these same winds over the crest.

Snow, unlike water, falls to the ground as a light fluffy solid and for this reason may be picked up by the winds and drifted over the crest of divides. Thus, for instance along the peak of a house we find that the heaviest snow is on the leeward side of the roof. On a mountain, in a

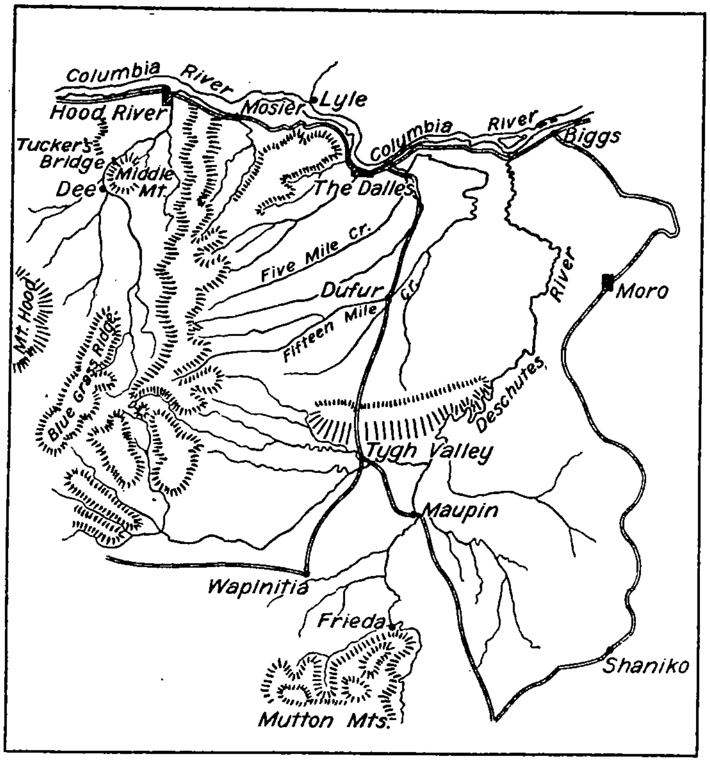

FIGURE 1.—The Dalles formation. This formation is composed of material derived from the Cascade Mountains and is evidence of a time when the water and ice supply was abundant. In The Dalles formation are glacial erratics that prove that glaciers from the Cascade Mountains extended far to the east

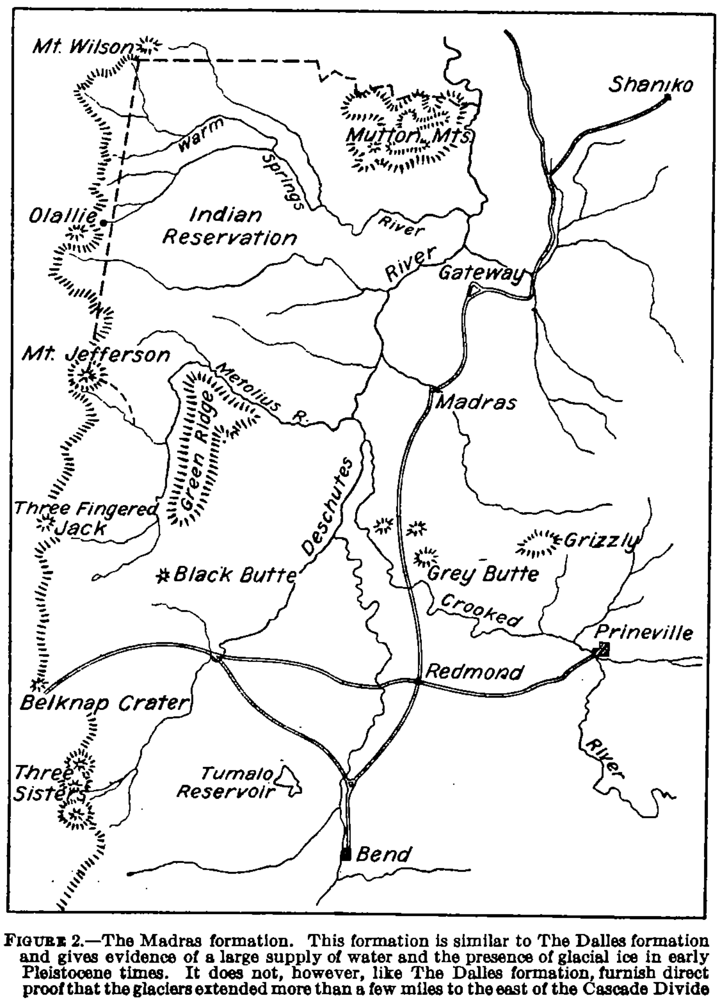

FIGURE 2.—The Madras formation. This formation is similar to The Dalles formation and gives evidence of a large supply of water and the presence of glacial ice in early Pleistocene times. It does not, however, like The Dalles formation, furnish direct proof that the glaciers extended more than a few miles to the east of the Cascade Divide

similar fashion, most of the snow is drifted to the leeside. Further, the higher the mountain, the further leeward the cloud banner will soar. Hence, if a range is high enough so that all precipitation occurs in the form of snow, much of it will drift over the divide. One would expect, therefore, that during the glacial period great glaciers must have been on the east side of the mountains of the Cascades. Existing evidence on such mountains as

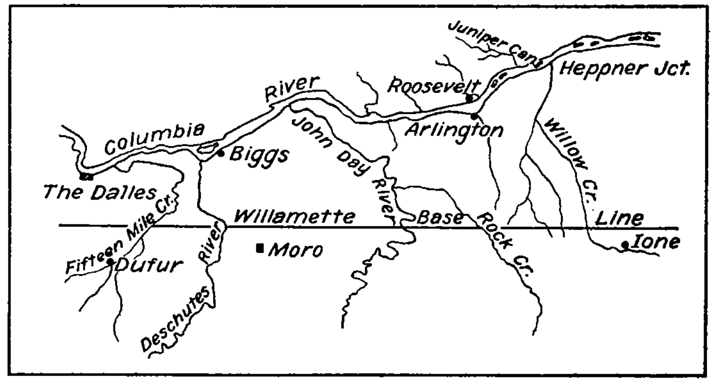

FIGURE 3.—The Arlington Lake beds contain both lake beds and stream gravels and furnish evidence of a period of extensive flooding of the Cascade Range at a time contemporaneous with the deposition of The Dalles and Madras formations. The Arlington Lake beds lie beneath extensive morainal deposits and bear on their surface enormous glacial erratics

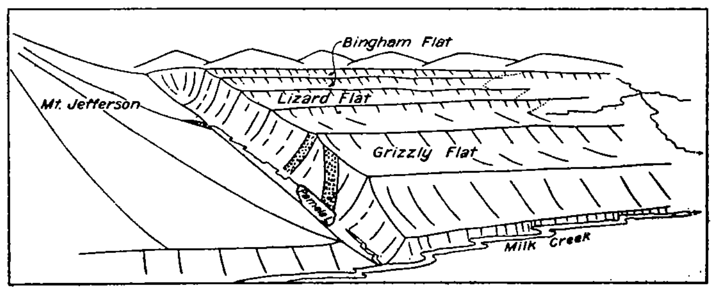

FIGURE 4.—Lizard Flat, Grizzly Flat, and Bingham Flat. These flats were formed by truncation of the upland lying east of Mount Jefferson. These glacially formed flats are now separated from Mount Jefferson by glacial valleys that lie almost at right angles to their slope. They give evidence therefore of two periods of glaciation in the Mount Jefferson region

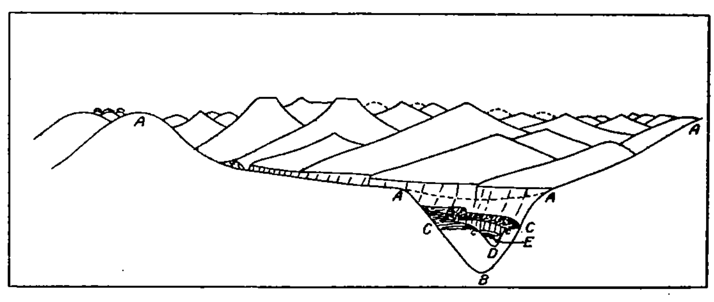

FIGURE 5.—A diagram to show the habitual valley profiles found on the west side of the Cascade Mountains. These profiles show at least five stages, as follows: AA, open shallow valleys; ABA, which were incised in stage II by deeper valleys CccC, these deep valleys were then aggraded to a high level in stage III

Mount Hood, Olallie, Jefferson, Three Fingered Jack, Washington, and the Three Sisters prove that this was so.

Nearly one-third of Mount Jefferson was cut away from its east side by great Pleistocene glaciers. On the east side of Black Crater, North Sister, Middle Sister, South Sister, and Broken Top an immense glacier extended far to the east beyond the present timber line. Over this area the rocks are intensely scoured and heavily mantled with glacial deposits. Only a half-cone of the Middle Sister, with the flat face to the east, remains from erosion during the ice age. All of the Elder Middle Sister was cut away with the exception of that standing beneath the cone of the present Middle Sister. The bergschrund wall cut by the former glaciers rises almost perpendicularly for 1,200 feet.

There are several facts which prove that East Fork of Hood River was not in existence at that time. Suffice to point out here that had it been in existence the following should be true: (1) The valley would be glacially carved throughout its entire length; (2) the side walls would show evidence of a glacier passing over them and rounded them; (3) there would be no hanging glacial troughs like Crane Prairie and Bonney Meadow.[1]

Dealing with the same area, we find evidence of a Stage III. The glaciers of the first epoch must have retreated at least to Blue Grass Ridge, and water which escaped from them, dammed by recessional moraines and perhaps lava flows, was diverted northward toward the main Hood Valley. The glacier held its restricted position long enough to cut a valley 3,000 feet deep.

Continuing to fix our attention on the same area, we find positive proof of another glacial advance and stage IV. This glaciation was not as extensive as the former. The ice advanced on the east side of the East Fork of Hood River and moved down it for several miles. The east-side glaciers did not cut a glacial valley long enough to open up into the older main glacial valley of Hood River.

Stage V is shown by the cessation of glaciation. Since that time the glaciers have diminished and now form tiny patches on the east slope of Mount Hood.

The five stages shown by The Dalles formation and the country east of Mount Hood is also shown farther south on the east side of the Cascade Mountains.

South of the Mutton Mountains is the Madras formation. (Fig. 2.) This formation extends southward almost to Bend, Oreg., and lies west of the Deschutes River and beyond its junction with the Crooked River and it lies west of the latter. The Madras formation closely resembles The Dalles formation. Its component beds lie almost flat. These consist of torrential beds of sands, gravels, pumice,and pyroclastics which lie between very uniform basaltic and andesitic lava flows. These flows have sealed in the torrential beds and serve as a protection for them. Toward the Cascade Mountains the uppermost lava flows become andesitic. The Madras formation fills structural and erosional depressions that are younger than the Columbia River basalt formation. No glacial erratics have been found in the Madras formation, but the gravels contain the same rocks and in about the same proportion as in the moraines which lie farther west. This formation has been examined during the field season almost daily over a period of three years and so far no erratics have been found. The torrential nature of the formation leads to the opinion that it is strictly a torrential deposit made by great quantities of water from streams that were forced to aggrade on a large scale in depressions. In fact, it looks as though sheet-water aggradation took place over a large area on the eastern side of the Cascade Mountains.

If the Madras and The Dalles formations are equivalent in time both may represent aggradational activity during the first glacial stage. In support of this conclusion let us now examine the Arlington Lake beds. (Fig. 3.) These beds occur on the south side and very close to the Columbia River. They are best preserved between Willow Creek and Blalock Canyon. They form beds not over 200 feet thick that lie perfectly flat. They consist of excellently bedded white ash, diatomaceous material, and gray silts. The bottom members contain 1 to 6 inches of water-worn pebbles, many of which are derived evidently from the Cascade Mountains. These beds are greatly eroded, but they once extended as far south as the Willamette base line, as far north as the north side of the Columbia River, an unknown distance east, and as far west as The Dalles beds, since they, too, lie absolutely flat. The Arlington beds are the result of some sort of ponding not long ago.

Observers over several years who have examined The Dalles, Madras, and Arlington beds have all become convinced that they were formed at the same time and by the same agency. The conviction prevails that they represent a period of aggradation during the first glacial stage.

The Madras and The Dalles formations thus give evidence of two climatic stages. Deep canyons cut in all of these formations show Stage III. These canyons indicate a rejuvenation process. Since all the beds of the three formations lie nearly flat, the canyon cutting is not due to any local uplift. Various explanations can be suggested but one not involving change of level would explain the change from aggradation to degradation. For example, if a glacial stage disappeared the amount of water in comparison to the amount of débris given to the stream would have been augmented, the transportation power of the streams accelerated, and canyons would have been cut.

It is not necessary, in support of the thesis of this paper to agree with the explanation given in the above paragraph. It is essential here to note that the age of the canyons is post The Dalles formation. These canyons and the upland surface on either side contain glacial erratics. The erratics are postcanyon and represent the last glacial stage.

These erratics consist of old weathered basalt, limestone, boitite-granite, granite-gneiss, quartzite, schist, and slate. They lie on only the surface of The Dalles and of the Arlington Lake beds, and despite our extensive studies such glacial erratics of these rock types have never been found within The Dalles or Arlington beds. The glacial erratics within these beds are of Cascade Mountain origin whereas those that lie on the surface are of foreign origin. Furthermore, the erratics within the beds are found no farther east than Five Mile Creek, in the vicinity of The Dalles.

The glacial erratics that lie on the surface have been found on both sides of the Columbia River from Willow Creek, Oreg., to The Dalles. On the John Day River they have been found as far south as Buckskin Canyon, T. 4 S., R. 18 E., elevation 1,000 feet. They are also quite common from McDonald to the mouth of the Columbia River. A large erratic of granite 5 by 2 feet and other smaller ones were found as far south as Sherar Bridge, on the Deschutes, practically as far south and at the same elevation as the occurrence on the John Day River. They were found rarely, however, from Sherar Bridge to the mouth of the Deschutes River. If the John Day and Deschutes Rivers were flooded so that the flood in their lower portion reach to their 1,000-foot contour, then such a flood would rise over the south rim of the Columbia River canyon from Willow Creek to The Dalles. Without attempting to discuss the subject fully, it is evident that flooded water conveying ice blocks bearing glacial erratics occupied these canyons at a date later than the canyons and later than The Dalles and Arlington beds. They definitely prove a later glacial stage.

[1] There is some evidence that the events of this first stage were even more complex and that great flows of andesitic lava poured eastward, burying in part The Dalles formation. The study on this phase of the problem is not complete.

On the walls of the canyons of three streams gravel bars are perched, and on the Columbia River there are in addition perched deltas. These high bars may also be related to this last glacial stage. Mastodon bones were found in one bar opposite Fargher, proving their Pleistocene or Pliocene age. These high bars and deltas may be properly related to the same glacial stage as the erratics.

The history recorded since that time is one of aggradation.

A summary of the evidence thus far presented shows five stages wherein the climate changed. These changes are (1) from the closing Pliocene to (2) an early glacial state, (3) to an interglacial stage, (4) to a second glacial stage, (5) to a recent aggradational stage.

CASCADE MOUNTAIN UPLAND

Evidence in support of glacial stages was first found by the writer and reported [2] as early as 1925 on the Cascade Mountain upland. Here, in addition, there is further proof of glacial stages.

There is abundant evidence of an extensive glaciation above 4,500 feet on the Cascade Mountains extending at least from Crater Lake on the south to Mount Hood on the north. The numerous peaks, even the small ones like Olallie Butte, bear large cirques, usually on the east side. The larger peaks are badly dissected and, in the case of some of them, like the North and Middle Sisters, are more than half destroyed. The surface of the plateau proper bears many roches moutonnées, erratics, moraines, and striæ. In the vicinity of Diamond Peak, Three Sisters, Mount Jefferson, and Mount Hood, where the writer has made his most detailed studies, the evidence points to a continuous mass of ice covering the entire upland surface. The fact of this extensive glaciation was first described by the writer.[3]

We will describe the evidence of glacial stages beginning with Mount Hood. North, northwest, and west of Mount Hood are glacially carved valleys and glacial deposits now separated from Mount Hood by more recently cut valleys and by thick aggradation deposits. Thus, upper Hood River Valley is of glacial form and its lower end, where constricted by Middle Mountain (see fig. 1) contains an old buried moraine. This moraine was traced as far north as Tucker's Bridge. The valley is separated from Mount Hood by later lava flows and aggraded sediments which in turn are cut by stream valleys.

Bull Run Lake is northwest of Mount Hood, lies in a typical glacial valley, and is dammed in by a moraine. The extension of that valley may be traced toward Mount Hood only as far as Sentinel Peak and Hiyu Mountain. The intervening distance of 7 miles is an area now deeply dissected by streams, the chief ones of which lie athwart the older drainage system. The west fork of Hood River and the Clear Fork of Sandy River, in fact, lie so contrary to the normal drainage slopes that some reason must be assigned for their abnormal position. On Sandy River morainal material may be traced almost to Cherryville.

In the case of Hood River Valley and the old Bull Run Lake Valley the glacier must have retreated far up the sides of Mount Hood. The water from the diminished glaciers was dammed by moraines and forced to flow a long way around to find an outlet. These diverted streams attached themselves to Hood and Sandy Rivers and have since realtered the older glacial topography.

In Hood River Valley we have further proof of this interglacial stage. Thus, from the junction of the Middle and West Fork of Hood River to Tucker Bridge bedded water-worn gravels and sands lie on top of morainal material. These torrential deposits do not lie on a hummocky morainal surface, but upon a smooth eroded plane, proving that the interglacial stage existed long enough not only to deposit an extensive valley fill but to cut away what must have been a large terminal moraine.

Two types of evidence exist, proving that a second glaciation took place in the Mount Hood region. First, near Dee, in Hood River Valley, glacial till lies on top of the interglacial beds. This last till is quite widespread and can be traced from Dee up all the branches of Hood River Valley.

The glacier of the second stage advanced down the newly formed V-shaped valleys but not as far as those of the first.

These glaciers cut the glacial valleys of East Fork of Hood River, White River, Salmon River, Zigzag, and Sandy Rivers. Only in the last two valleys did the glacier reach an earlier glacial valley. In fact only in the last two cases were the valleys that were cut by interglacial streams occupied by glaciers.

Since the second glacial stage the general events have been aggradation, accompanied by a retreat of the glaciers,[4] there have been minor glacial fluctuations. Thus, White River Valley shows in its upper portion morainal material covered with a 10-foot bed of soil. Lying on the soil are trees up to 1½ feet in diameter. This jumble of trees is now overlain by a 250-foot thickness of fluviatile material.

The five climatic stages so clearly shown in the vicinity of Mount Hood are found in other parts of the Cascades.

One evidence of this great ice cap is to be found about Mount Jefferson. Here the evidence is clear that the valleys were all filled to overflowing by one immense and continuous glacier which moved eastward and westward over the entire surface. In the early Pleistocene, instead of many individual or isolated glaciers surrounding Mount Jefferson, one great glacier entirely mantled its slopes and extended outward to a distance of 10 miles and down the valley for 20 miles. Only a few of the highest of the surrounding peaks were overtopped by this ice.

Another proof of this great Pleistocene glacier is the surface of Grizzly, Lizard, and Bingham Flats, near Mount Jefferson. (Fig. 4.) Standing on the west side of Mount Jefferson and looking to the west one notes that Hunts Cove and Hunts Cove Creek Valley is a distinct glacial valley extending north and south. Likewise, the Marion Creek fork of the Santiam is a typical north and south glaciated valley. Between these two great north and south valleys are Grizzly, Lizard, and Bingham Flats. Grizzly Flat, for instance, is not one continuous flat surface, such as one might expect from

[2] Hodge, E. T. Geology of Mount Jefferson, Mazama, December, 1925, Vol. VII, No. 2, pp. 26-58.

[3] Hodge, E. T. Mount Multnomah, Univ. of Oreg. publication, 1925.

[4] Glacier studies in the Cascade Mountains have been limited in quantity and devoted exclusively to Recent glacial features.

1. Coleman, E. T. Glaciers in Oregon and Washington, Alpine Jour., 1877, p. 233.
2. Fairchild, H. L. Evidence of Ice Erosion from the Cascades, U. S. G. Soc. Amer. Bull. 16: 39-41, 1905-6.
3. Hodge, E. T. 1925, loc. cit.
4. Reid, Harry Fielding. Jour. Geol., p. 261, 1904.
5. Russell, I. C. U. S. G. S. Bull. 252, p. 124, 1905.
Glaciers Existing in U. S., Oregon, U. S. G. S., 5th Annual Report, pp. 339-341, 1883-84.
Glaciers of North Amer., Ginn & Co., pp. 67-70, 1897. Notes on glaciers on Mount Hood, also Mounts Jefferson, Diamond Peak, and Three Sisters.
6. Stadter, F. W. Mazama Annual, 1925.
7. Williams, Ira A. Glaciers of the Three Sisters, Oreg., Mazama, 5: 14-23, December, 1916.

its name, but a series of gentle troughs, the axes of which extend east and west, as shown in Figure 4. A glacier evidently moved directly west over any preexisting divides and plowed these broad, gentle furrows. This glacier must have been 2,000 feet deep in order to move over and truncate such high divides. Grizzly Flat, Lizard Flat, on the west, Bingham Basin on the southwest, the flat between the middle forks of Jefferson Creek on the southeast, and a number of smaller flats at the base of the mountain on the northwest, west, and southwest were planed by this early Pleistocene glacier.

Because the west side of the Cascades was more dissected by stream valleys than the east side, tongues from the ice sheet were concentrated in long glacial streams which moved down these valleys for long distances. The total surface covered by ice was, however, much less than on the east side of the "break." On the west side of Mount Jefferson the glaciers extended as far west as Detroit and reached an elevation of 2,300 feet.

The evidence in the Mount Jefferson region of an interglacial stage is similar to that in Mount Hood in regard to the east fork of Hood River. The profiles characteristic of the lower valleys and which reveal the climatic stages, of course, are not to be found in the upper valleys or along the crest of the Cascade Range. However, in these higher elevations there is evidence that older glaciated surfaces were at a later time free of ice and eroded by streams. Thus, Hunts Cove Valley, on the west side of Mount Jefferson, is incised in the high surface of and early glacial planation represented by Grizzly, Lizard, and Bingham Flats. This older upland glacial surface may be called the first glacial surface.

The Hunts Cove valley must be younger than the first glacial surface, because a topographic unconformity exists between its valley walls and the older upland glaciated surface. A glacier moved westward from the divide across this upland and planed it. It then retreated, forming moraines, behind which its waters were diverted. The diverted waters cut new valleys almost at right angles to the former glacial course. The glacier, upon readvancing, followed the new valleys and glaciated them.

Jefferson Park is another bit of evidence of an interglacial epoch. Beyond the ridge anchored by east and west Park Butte there is abundant evidence that at one time ice moved northward for several miles before swinging west and east down the Cascade slopes. This evidence is that of striæ, roches moutonnées, and moraines. If Jefferson Park had been in existence during this period of glacial erosion, it is evident that, due to the steep east and west slopes, most of the ice would have moved east and west and cut the valley so deep that none would have overridden the east and west Park Butte Ridge. The valley must have been cut later and in a manner similar to that of Hunts Cove.

The same stages have not been observed in the Three Sisters region, but there is evidence of an early extreme glaciation. For instance, all the area on the south side between the South Sister and the Rampart shows evidence of glaciation. Here much of the glaciated surface is concealed by young lava flows called Rock Mesa, Devils Hill, and Newbery Flow. Nevertheless, at the edge of Rock Mesa one can see where the lava poured out over glaciated rocks. Again, to the north of the Three Sisters where "islands" rise through Belknap and Jerry Flows, the surface of these "islands" shows glacial striæ. If one could remove the great McKenzie lava flood which covers most of this area one would find, no doubt, beneath it roches moutonnées, polished rocks, striations, and glaciated bowlders. A great glacier covered the west side of the Three Sisters through which only the large peaks emerged. The great cirques and glacially carved walls indicate that this glacier extended westward, abutting against the Husband, which, acting as a cleaver, split this glacier in two parts, one part of which moved down Lost Creek Valley and the other moved down Separation Creek Valley. The west side of the Husband bears large cirques, and the area beyond is glaciated for about 5 miles. To the north a great stream of ice moved down the Santiam as far west as Cascadia on the south fork of the Santiam. Thus, the last moraine on the middle fork of the Willamette is at Rigdon, at 2,445 elevation, and on the McKenzie rim, at Belknap Springs.

VALLEYS ON WEST SIDE OF CASCADE MOUNTAINS

The evidence now to be presented has to do with profiles of and deposits in the valleys on the west side of the Cascade Mountains. The time at which the five post-Pliocene stages occurred are not known except by such correlation with the glacial stages just cited.

The correlation attempted depends upon the interpretation made of the valley profiles. Were the streams aggrading or degrading during the periods of mountain glaciation? In seeking an explanation by comparison with other parts of the world we must remember that we are dealing with streams that had their origin in mountain and not continental glaciation. These streams also were influenced by changes in gradient. Unlike the streams on the east side of the Cascades, these had a comparatively free outlet to the sea. Further, there is the factor that a stream may degrade in one portion of its course and aggrade in another during the same period of time. For the purpose of this paper an assumption is made which it is hoped future discussion will justify. It is assumed that the cause of glaciation was increased rainfall, resulting from an uplift of the Cascade Mountains. The ice resulting from this increased rainfall inhibited general mountain erosion to such an extent that the streams, with their increased gradient and water supply, were able to engage in erosion. During interglacial stages, for the same reason, rainfall was decreased and streams were supplied not only with débris then freed from the glaciers but by the material furnished by renewed upland erosion. The reduced rainfall and gradient and increased débris caused the streams to aggrade.

Before the glaciers appeared—that is, at the close of the Pliocene—the upland surface had been subjected to a long period of erosion. The valleys produced valley profiles AA, in Figure 5. This represents stage I, a period of comparatively smaller precipitation. The advent of glaciation, stage II, greatly increased the erosion power of the stream.

The rivers had cut deep gorges in the bottoms of the Pliocene valleys. These gorges, incised in still older valleys, may be seen in all parts of the Cascades and represent that portion as shown in Figure 5 from ABA.

Great rainfall, which produced the glaciers of the first stage and deepened the valleys of the Cascades and Coast Range, carried to the sea great volumes of débris. At the end of this time there must have been left on the higher slopes large amounts of wasted material eroded but not entirely removed. The gradient of the stream having been reduced, the decreased rainfall of the interice stage caused the streams to aggrade their valleys with the material brought to them by the mountain streams of high gradient.

In the valleys of the McKenzie, the Santiam, and other valleys of the Cascades definite evidence is given of the aggradation on the west side of these valleys, as indicated in Figure 5 CccC. Thus, this aggradation begins in the Santiam at about the mouth of Tunnel Creek. Here, about 9 miles from Detroit and at an elevation of 2,400 feet, the valley is broad and low terraces occur on either side of the stream. These silts and gravels accumulated in the Santiam may be traced along the sides of this valley to its mouth as benches.

Following this reasoning to its logical conclusion, we may explain CDC in Figure 5 by a redevelopment of those conditions which produced glaciation, such as increased precipitation. Because of the increased size of the glaciers and increased rainfall at lower elevations the streams again became swollen. The increased volume of water permitted the streams to again engage in down cutting in all the valleys on the west side of the Cascades. Thus, west of Mount Jefferson the results of this down cutting are to be noted in the river-cut terraces along the streams. The streams were able to remove much of the material deposited in their valleys, in some places all down to bedrock, and in other places the streams were superimposed on side-wall spurs, but in most places only terraces were cut in the older flood plains.

In Recent times, with the decrease in precipitation and the shrinkage of the glaciers, the eroding and transportation power of the streams has diminished. The streams on the west side of the Cascade Mountains are all overloaded and are again filling their channels with muds, sands, and gravels (fig. 5, D–E) but have not as yet had time to fill their valleys up to the level of interglacial times. On the steeper slopes the gradient and volume of the stream is sufficient, as a yearly average, to enable the streams to erode. This is shown by notches cut in the edges of the glacial steps.

WILLAMETTE VALLEY

The evidence of five stages in the Willamette Valley, each correlated with those so far described, is almost identical with its tributary valleys on the west side of the Cascade Mountains. The thalwags of the Willamette Valley are identical with the mountain valleys, but the former are much more difficult to detect.

The interglacial aggradational stage has left an interesting record. The Willamette Valley at Portland was aggraded to 300 feet above the present river level. Along the Valley near Portland are important terraces. Terraces are uncommon in the upper valley, but here and there, perched on the valley walls, are small river deposits. The height of aggradation is shown by waterworn pebbles and gravels which may be found lying on the top of the many isolated buttes which stand in the valley. Thus, on Skinner, Honeysuckle and Gillespie Buttes near Eugene the gravels were first noted by the writer lying at 100 feet above the present valley floor. Bretz [5] has described a Satsop formation to which he assigns the gravels along the Columbia River, on the Sandy River, and elsewhere in Oregon and in many places in Washington. His description is typical of gravel terraces common along all the rivers in western Oregon. Those described by Bretz, in Oregon, and all others examined by the writer lie in rock-bound valleys and can be no other than the deposits made by stream aggradation during an interglacial stage.

Much of this aggraded material was removed by the swollen waters of the succeeding ice stage. The material eroded from the upper valleys was carried downstream and deposited at the coast or in the slack waters of the lower river. The Columbia River was particularly overloaded because of immense deposits of aggraded material east of the Cascade Mountains. The high flood waters due to choking of the lower course of the Columbia and due to periodic floods (produced when warm, heavy rains fell on the great glacier and snow covered uplands) were high enough to reach the rim of the valley walls. Floods of about 50 feet are common even at the present time, and the river lies 300 feet below its former level at Portland. In an ice age, with a river choked in its lower course, floods may have been high enough to pond all the main river between Columbia, Deschutes, and John Day, in Oregon.

The fact of the flooding has been observed before; but the date of it has never been fixed, and the cause has been explained as subsidence.[6] The complete absence of marine or brackish-water fossils seem to eliminate the subsidence theory.

Glacial erratics occur in the Willamette Valley lying on top of the terrace deposits. They are found nearly as far south as Eugene. The materials are of rocks not known to occur either in the Cascade Mountains or the Coast Range of Oregon and are identical with similar erratics found along the Columbia River east of the Cascade Mountains. The most probable theory as to their origin seems to be as ice-floated erratics derived from glaciers in the upper Columbia River Valley. Their deposition was concurrent with the erosion of terrace deposits at the time of the second glacial stage.

The fifth climatic change in the Willamette Valley is shown by the present aggradational work of the streams resulting from a reduced amount of precipitation.

If we now compare the valleys on the west side of the Cascade Mountains with those on the east we find them presenting the same evidence, with two exceptions. The valleys on the east side of the Cascade Mountains do not show the Pliocene and early Pleistocene profiles, because they are now buried beneath the great aggradational deposits of the Madras and The Dalles formations. There is sufficient evidence, however, that these deposits do fill erosional depressions probably cut at these periods. The greater extent and thickness of the deposits on the east side may be accounted for by two conditions—one, that the valleys on the east side, unlike those on the west, had no convenient outlet to the sea, and, two, the streams on the east side, for reasons already cited, were supplied with a greater supply of glacial débris.

OREGON COAST DEPOSITS

The amount of precipitation over an area at a given stage of elevation determines the amount of erosion and transportation that will take place. If the precipitation is great the stream will erode the uplands and carry all

[5] Bretz, J. Harlan. Journ. Geol., XXV, No. 5, pp. 446–459, 1917.
The late Pleistocene Submergence in the Columbia Valley of Oregon and Washington, Jour. Geol., vol. 37, No. 7, October–November, 1919.
The Satsop Formation of Oregon and Washington, Jour. Geol., 25:446–458, July–August, 1917. Abstract, Geol. Soc. Amer. Bull. 28:170–71, Mar. 31, 1917.

[6] Condon, Thomas. The Willamette Sound, The Overland Monthly, 7:468–473, 1871. (A chapter from Two Islands.)
The Two Islands and what became of them. Portland, Oreg., 1902.
Oregon Geology, a revision of The Two Islands, with a few tributes to the life and work of the author, by Ellen Condon McCormack. 2d ed. Portland, Oreg. J. K. Gill Co., 1910.
Collier, Arthur J. The Two Islands, Univ. of Oreg. Monthly, 8:48–50, November, 1902, No. 2. A review of Professor Condon's book.
Smith, W. D., and Packard, E. L. Salient features of the geology of Oregon. Univ. Oreg. Bull., n. s. 16, No. 7, 1919.
Jour. Geol., 27:79–120, 1919.

of their load to the sea; if small, the load will be deposited in the valleys and very little material will reach the sea. Therefore, of the five stages here considered, there would have been no deposits made along the Oregon coast during three of them. Only during the two ice stages would the streams have carried their entire load to the coast.

The deposits which may be assigned to these two glacial stages, and the break between them, have been noted by several observers.[7] Diller, Arnold and Hannibal, and Martin observed the deposits at the mouth of Elk River and gave to them a Pleistocene age. A difference of opinion exists between these observers as to the early or late Pleistocene age of these deposits—a difference of opinion quite natural in view of the fact that a disconformity exists between the lower shell, sands and gravel beds (10 to 100 feet), and the upper gravel beds (5 to 15 feet). These same beds are found at several places along the coast as far north as the Columbia River.

At Cape Blanco, J. P. Smith, Martin, and W. D. Smith and E. L. Packard have described two formations overlying the Pliocene Empire formation. The lower or Cape Blanco beds are composed of shell beds, conglomerates, and sands. Disconformably overlying these is the "Elk River" beds of Martin and Arnold and Hannibal. The author thinks the Cape Blanco here is the equivalent of the lower Elk River beds at Elk River and the equivalent of the lower set of beds unnamed at other places along the coast. The "Elk River" at Cape Blanco corresponds to the upper portion of the Elk River elsewhere.

EASTERN OREGON LAKES

Finally, and in brief, one lake at least shows evidence of these five stages. Fossil Lake contains fossils of Pleistocene age [8] consisting of fish, camels, horses, mammoths, birds, and other animals. These have been found by the writer to occur in two distinct groups and to lie, respectively, in two different lake levels. Since no fossils of pre-Pleistocene age have been found, we may presume that the lake came into existence with Cascade Mountain glaciation, as follows: The largest glaciers were on the east side of the Cascade Mountains. The winter winds then and now are the rain bearers, but the present summer winds are undersaturated. The summer Pacific Pleistocene winds, nearly saturated, were completely saturated in passing over the glaciers, melting in the hot summer sun.

These saturated summer winds moving eastward over the high plateaus of eastern Oregon were disturbed by the rising convection columns of air produced on this high flat area. The saturated winds descending from the melting glaciers were mixed with rising convection currents brought to saturation by decrease in temperature of air. This mixture of saturated air masses of different temperatures would give rise to summer cyclonic thunderstorms, such as are now common in the vicinity of the Blue Mountains of Oregon and in Colorado during the month of August. By reason of the moisture added by the glaciers these mixed currents of air were capable of yielding more moisture than at the present time and consequently gave rise to great lakes in eastern Oregon. Such lakes would correspond to the ice stages, and from the last ice stage to the present time Fossil Lake, in harmony with all of Oregon, has desiccated; it is now completely dry and imminent to burial by the surrounding desert sands.

CORRELATION

The correlation of these five stages must be based to a large extent upon the mechanics involved and which have already been stated. There is not sufficient evidence to warrant correlating these stages with other Pleistocene epochs on the Pacific coast. In British Columbia, Dawson,[9] and in the State of Washington, Willis,[9] and Bretz [9] have found definite evidence of only two periods of glaciation, separated by one interglacial period. Matthes [9] has noted the same epochs in the Sierra Nevadas. In the Oregon Cascade Mountains and at the above localities the first ice epoch is very much older than the second ice epoch. This is shown by the weathered glacial surface, the decayed moraines, and its deep burial below the deposits of the interglacial epoch. So far no definite evidence has been found which definitely proves that this older glacial epoch was not preceded by still earlier glaciations. Because of its extensive and intensive character it may have destroyed so much of the evidence of earlier glaciations that their existence may not be proven without more detailed searches being made.

The best chance of making a correlation is with the glacial epochs in Washington, and it may be that the three Pleistocene stages noted in Oregon are identical with the Admiralty (oldest ice epoch), Puyallup (interglacial epoch), and Vashon (youngest glacial epoch) of that State.

Until such a time as a complete correlation can be made it is proposed to call these epochs as follows:

Recent—period of aggradation and small precipitation.
Jeffersonian—epoch of glaciation and great precipitation.
Williamettian—epoch of aggradation and comparably small precipitation.
Cascadian—epoch of glaciation.
Late Pliocene—epoch of erosion and small precipitation.

The Jeffersonian epoch may be identical with the Wisconsin of North America. The glacial erratics in the Willamette, Deschutes, John Day, and Columbia River Valleys are not referable to any known Oregon source. If they were furnished by the continental glacier of Northern Washington and British Columbia they must have been furnished at Wisconsin time and thus gave to Oregon one tie with continental glaciation.

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[7] Arnold, R., and Hannibal, H. Proc. Amer. Phil. Soc., vol. 52, p. 595, 1913.
Duller, J. S. U. S. Geol. Survey Bull., 196, p. 31, 1902.
Martin, B. Univ. Calif. Pub. Bull., Dept. Geol., vol. 9, p. 245, 1916.
Smith, J. P. Proc. Calif. Acad. Sci., 4th ser., vol. 9, No. 4, p. 138, 1919.
Smith and Packard. Loc. cit., 1919.

[8] Cope, E. C. Am. Natural. XXXIII, 970–82.
Condon, Thos. Referred to by Smith and Packard, 1919, loc. cit.
Shufeldt, R. W. Jour. Acad. Nat. Sci., Philadelphia, No. 9, 1892.
New and extinct birds and other species from the Pleistocene of Oregon, Sci. New Ser., 37:306–307, Feb. 21, 1913.

[9] Bretz, J. Harlan. 1908, 1913, loc. cit.
Glaciation of Puget Sound, Bull. Wash. State Geol. Survey, No. 8; Bull. No. 13, Wash. Geol. Survey.
Dawson, G. M. Physiographic Geology of the Rocky Mountain Region, Trans. Royal Soc. Canada, Vol. VIII, 1890, sec. 4, pp. 3–74.
Matthes, F. E. Science, p. 550, 1925.
Willis, Bailey. Physiography and Deformation of Wenache, Chelon Dist., loc. cit.
Drift Phenomena of Puget Sound, Bull. Geol. Soc. Amer., vol. 9, 1897. Willis first employed the terms Admiralty, Puyallup, and Vashon.